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Optimization of Multi-period Bilevel Supply Chains under Demand Uncertainty

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Abstract

Due to advance of global manufacturing, the decentralized optimization of multi-tier supply chains for multiple retailers and manufacturers becomes more and more important. Conventional works on game theoretical model for supply chain planning problems concentrates on single period models. However, the situations for decision making in decentralized supply chains are subject to change with respect to time periods. In this paper, we address the optimization of multi-period bilevel supply chains under demand uncertainty. The decentralized supply chain planning problem is modelled as a multi-period non-cooperative game. The problem is formulated as a stochastic multi-period bilevel optimization problem under demand uncertainty. The optimization algorithm to derive a Stackelberg equilibrium for multi-period bilevel supply chain planning problem is developed. The effectiveness of the proposed method is validated by comparing it with the single period models.

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Keywords: global supply chain, coordination, production planning, Stackelberg game, bilevel optimization, demand uncertainty

1. Introduction

With the progress of the global supply chain, members of the supply chain (SC) are widely spread to multiple companies in domestic or global countries. It is required to achieve the overall optimization of delivery as a whole SC from the procurement of orders, production and distribution. Conventionally, the SC optimization problems describe the entire SC as a single optimization problem and the methodology of obtaining solutions were common. However, in the global SC, considering the profit and contractual relationships among multiple companies, the establishment of the game theoretical approach is urgently needed in supply chain planning under uncertainties (Fig. 1).

Most conventional studies on the game theoretical approach assume that the SC configuration, i.e., members of the SC, the leader or follower relationship, terms and conditions are fixed or they are treated as constraints. In this paper, the SC configuration represents the configuration of product items, the contracted suppliers or retailers, leader or follower relationship, contract, trading conditions (rather than in the software components, not in the hardware part). In recent years, with the dismantling of the popular and business-to-business series of information systems. It has become to be able to select suppliers freely. In recent global SC, due to uncertainty and changes of new product development, changes in the trade and currency risk, uncertainties such as disaster risk, it is required to build reconfigurable SC that can flexibly respond to several changes minimizing the amount of resources as possible.

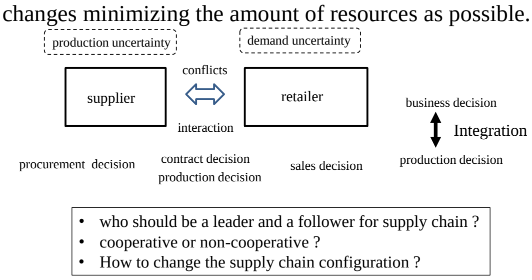

Fig. 1. Necessity of the game theoretical approach in supply chain planning under uncertainties

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Dynamic supply chain is a flexible SC that can change the suppliers for each contract without specific trading partners only with respect to conventional SC with the fixed leader or follower relationship. In this paper, we study a reconfigurable bilevel supply chain under that can change the leader or follower relationship. The bilevel supply chain consists of the suppliers and retailers with a leader or follower relationship.

The authors have proposed an optimization algorithm to derive the Stackelberg equilibrium solution for the bilevel SC that the supplier is a leader and the retailer is a follower. Zhang and Shi (2009) developed a multi-period production planning model [1]. Yoshida and Nishi (2014) presented a theoretical analysis of bilevel multi-period production planning problem [2]. Yoshida and Nishi (2015) presented an algorithmic procedure to derive a Stackelberg equilibrium for multi-period bilevel SC under demand uncertainty [3].

However, the above model does not consider reconfigurable SC that the leader or follower of the member of the SC can be flexibly changed. Therefore, newly formulated multiperiod bilevel level SC problem under demand uncertainty is required. In this paper, an algorithm to obtain a decision making of reconfiguration of bilevel SC, which determines who should be a leader or a follower of the SC, is studied. Considering the demand uncertainty, the objective function of the retailer is formulated as a nonlinear function. For the solution of the bilevel programming problem, the main issues are only related to a single period planning problem. However, the solution algorithm with a nonlinear bilevel problems in multi-period planning problems has not been studied so far. Therefore, in this study, for the Stackelberg equilibrium by a single supplier and a single retailer, we propose an efficient solution algorithm for multi-period bilevel production planning problem that takes into account the demand uncertainty.

2. Related works

Coordination of production planning for multiple companies is proposed by Nishi et al. (2008) [4]. Game theory is a well-known approach to achieve the coordination. Yu et al. (2009) improves members' profits of supply chain systems between a manufacturer and its retailers incorporating the inventory policy by a Stackelberg game where advertising, pricing and inventory replenishments are all involved [5]. The coordination of a supply chain consisting of a manufacturer and a retailer with return policy is proposed by Xiao et al. (2010) [6]. Yang et al. (2011) presents an assembly supply chain system consisting of one retailer and two suppliers with forecast updating [7]. Nagurney et al. (2005) have introduced a game theoretical approach for supernetworks in which supply-side and demand-side risk are included [8][9]. They derive Nash equilibrium of the supernetworks. Yin and Nishi (2014) presented a solution procedure for a mixed integer nonlinear formulation of the supply chain optimization problem with quantity discounts under demand uncertainty [10]. Yin and Nishi (2015) developed an optimal coordination for suppliers and manufacturer by using a Stackelberg equilibrium under demand uncertainty [11]. Zhang and Shi presented a multi-period multi-product newsvendor models with supplier discounts [1]. By utilizing the multi-period newsvendor model, Yoshida et al. (2014) investigated an analytical solution for multi-period production planning for single supplier and retailer under uncertain demands [2]. However, the analytical model does not always applied to the real problems. The problem to find the Stackelberg equilibrium can be formulated as a bilevel optimization problems [12]. Jiao and Tseng (2013) addressed a direct method to derive an equilibrium of bilevel optimization problems [13]. Du et al. (2014) introduces an interactive solution approach to solve the Stackelberg game theoretic model for joint optimization of the product family configuration and scaling design [14]. Yoshida and Nishi (2015) presented an algorithmic approach to solve the multi-period bilevel supply chain consisting of single supplier and single retailer [3]. However, the multi-period SC reconfiguration problem which can change its leader or follower relationship has not been considered in the prior works.

3. Multi-period dynamic supply chain

3.1 Dynamic supply chain

Dynamic supply chain stated here is a reconfigurable supply chain that can change its contracted partners, cooperative or noncooperative relationship dynamically. In this paper we assume a multi-period bilevel supply chain that can change its leader and follower relationship dynamically with respect to time periods.

3.2 Problem description

In this study, we consider a single supplier and a single retailer of a multi-period bilevel production planning problem shown in Fig. 2. We assume that there is a leader or follower relationship between them in order to respond quickly with uncertain situations. In the model, the supplier determines its production quantity and inventories for multi-products in order to maximize the total expected profit under demand certainty. The retailer determines its distribution planning and the order quantity to the supplier under demand uncertainty when the wholesale price is given. The inventory balancing constraints should be satisfied for multi-period planning both for the supplier and the retailer. The timing of production, order quantity, inventory balancing are represented in Fig. 3. The demand of customers as normally distributed, make decisions to maximize the expected value of the own interests. As well as producers, inventory that occurred in a certain period shall be carried over to the next. Also, if the product shipments there period does not satisfy the demand of customers, it is assumed to bear a lost opportunity penalties.

The decision-making for suppliers and retailers is done through multi-periods. It is assumed that to make decisions based on the Stackelberg game, in particular, the leader and the follower relationship can be changed according to the situations. Fig. 2 shows the relationship between the supplier and the retailer.

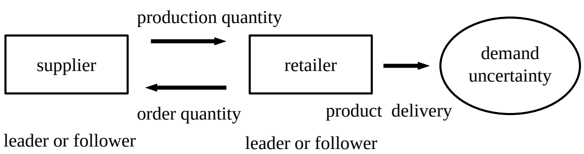

Fig. 2. Two-tier supply chain with supplier and retailer.

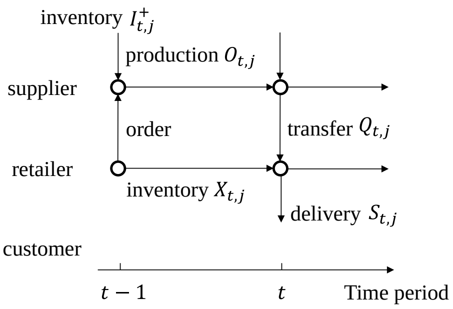

Fig. 3. Multi-period model.

3.3 Problem formulation

The multi-period supply chain planning problem with a single supplier and a single retailer under demand uncertainty is formulated as a bilevel programming problem.

Sets:
J: set of product items
T: set of planning periods

Parameters:
c_{tj}: production cost for item j in period t
g_{tj}: opportunity loss cost of item j in period t for retailer
h^s_{tj}: inventory holding cost of item j in period t for supplier
p_{tj}: sales price of item j in period t
s_{tj}: setup cost for item j in period t
w_{tj}: wholesales price for item j period t
M: a sufficiently large constant
h^r_{tj}: inventory holding cost of item j in period t for retailer
z_{tj} : random variable representing demand of item j in period t following normal distribution $N(\mu_j, \sigma_j^2)$ where μ_j is the average of demand of item j and σ_j^2 is the variance of demand of item j.

Decision variables:

Supplier
O_{tj}: production quantity of item j in period t
I^s_{tj}: inventory quantity of item j in period t for supplier
x_{tj}: binary variable that takes 1 if product item j is changed in period t, and 0 otherwise
y_{tj}: binary variable that takes 1 if product item j is produced in period t, and 0 otherwise

Retailer
Q_{tj}: order quantity of product item j in period t from retailer to supplier
I^r_{tj}: inventory quantity of item j in period t for retailer,
S_{tj}: delivery quantity of item j in period t from retailer to customers

$$\max J_s = \sum_{t=1}^{T}\sum_{j=1}^{J}\big(w_{tj}Q_{tj} - c_{tj}O_{tj} - h_{tj}I^s_{tj} - s_{tj}x_{tj}\big) \quad (1)$$

$$\text{s. t. } I^s_{tj} = I^s_{t-1,j} + O_{tj} - Q_{tj}, \ \ \forall t, \forall j \quad (2)$$
$$O_{tj} \geq Q_{tj} - I^s_{t-1,j}, \qquad \forall t, \forall j \quad (3)$$
$$\sum_{j=1}^{J} y_{tj} \leq 1, \quad \forall t \quad (4)$$
$$x_{tj} \geq y_{tj} - y_{t-1,j}, \qquad \forall t, \forall j \quad (5)$$
$$O_{tj} \leq M y_{tj}, \qquad \forall t, \forall j \quad (6)$$
$$O_{tj}, I^s_{tj} \geq 0, \qquad \forall t, \forall j \quad (7)$$
$$x_{tj}, y_{tj} \in \{0, 1\} \qquad \forall t, \forall j \quad (8)$$
$$\max J_r = \sum_{t=1}^{T}\sum_{j=1}^{J} E(RE_{tj} - IC_{tj} - UP_{tj} - w_{tj}Q_{tj}) \quad (9)$$
$$\text{s.t. } I^r_{tj} = I^r_{0j} + \sum_{t'=1}^{t}[Q_{t'j} - \min(z_{t'j}, S_{t'j})], \forall t, \forall j \quad (10)$$
$$RE_{tj} = p_{tj}\min(z_{tj}, S_{tj}), \qquad \forall t, \forall j \quad (11)$$
$$IC_{tj} = h^r_{tj} I^r_{tj}, \qquad \forall t, \forall j \quad (12)$$
$$UP_{tj} = g_{tj}\max(0, z_{tj} - S_{tj}), \qquad \forall t, \forall j \quad (13)$$
$$Q_{tj} + I^r_{t-1,j} - S_{tj} \geq 0, \qquad \forall t, \forall j \quad (14)$$
$$Q_{tj} - (O_{tj} + I^s_{tj}) \leq 0, \qquad \forall t, \forall j \quad (15)$$
$$Q_{tj}, S_{tj}, I^r_{tj} \geq 0, \qquad \forall t, \forall j \quad (16)$$

In the supplier's problem, decision variables are the production quantity O_{tj} of item j in period t and the inventory quantity of the products I^s_{tj}. y_{tj} is the binary variable which equals 1 if the supplier produces the product j in period t and 0 otherwise. x_{tj} is also the binary variable which equals to 1 if the supplier produces the different product in period t from period $t-1$. The objective function (1) is the sum of the wholesale profit $w_{tj}Q_{tj}$, the production cost $c_{tj}O_{tj}$, the inventory holding cost $h^s_{tj}I^s_{tj}$ and the setup cost $s_{tj}x_{tj}$. The constraints (2) express the inventory balancing constraints and the constraints (3) denote the production quantity. The supplier can produce only one type of product by the constraints (4). Constraints (5) represent the setup constraints. M is a large positive constant in constraints (6). Constraints (7) and (8) denote variable constraints. On the other hand, in the retailer's problem, the decision variables consist of the order quantity to the supplier Q_{tj}, the delivery of the products for the customer S_{tj} and the inventory quantity I^r_{tj} of item j. The objective function (9) consists of the sales revenue RE_{tj}, inventory holding cost IC_{tj}, the opportunity cost UP_{tj} and the wholesale cost $w_{tj}Q_{tj}$. In the problem, the customers demand is assumed to be uncertain. Therefore, RE_{tj}, IC_{tj} and UP_{tj} are represented by the expected values by the equation (11), (12) and (13), respectively. The constraints (10) are the inventory balancing constraints. The constraint (14) describes the upper bound of the delivery for the customers. The constraint (15) describes the upper bound of the order quantity. The constraints (16) denote the non-negativity of decision variables.

4. Solution approach

4.1 Reformulation of the expectation function

Section 3.3 shows the multi-period bilevel supply chain model. In the model, the retailer's objective function is calculated as the expected value because of the demand uncertainty. However, it is difficult to solve the retailer's problem by the experimental method if the customer's demand is assumed to depend on normal distribution.

Petkov and Maranas (1997) addressed the normalization technique of the expectation of the costs under demand uncertainty [15]. In their model, the retailer's objective function is reformulated by the normalization of the probability distribution. Therefore, in this study, we propose the reformulation of the retailer's problem by the normalization. In this case, the expected value of the sales revenue RE_{tj}, inventory holding cost IC_{tj} and the opportunity loss cost UP_{tj} are reformulated as (17), (18), (19) respectively.

$$RE_{tj} = p_{tj}\hat{z}_{tj} + p_{tj}\sigma_{tj}[-f(Y_{tj}) + (1 - \Phi(Y_{tj}))Y_{tj}] \quad (17)$$

$$IC_{tj} = h^r_{tj}[I^r_{0j} + \sum_{t'=1}^{t} Q_{t'j} - \sum_{t'=1}^{t}[\hat{z}_{t'j} + \sigma_{t'j}[-f(Y_{t'j}) + (1 - \Phi(Y_{t'j}))Y_{t'j}]]] \quad (18)$$

$$UP_{tj} = -g_{tj}\sigma_{tj}\left[-f(Y_{tj}) + \left(1 - \Phi(Y_{tj})\right)Y_{tj}\right] \quad (19)$$

In these equations, f is the probability density function and Φ is the cumulative distribution function. $\hat{z}_{tj}$ is the average of the customer's demand, σ^2_{tj} is the variance of the customer's demand. Also, Y_{tj} is defined by (20) and it is used in order to realize the normalization of the retailer's objective function.

$$Y_{tj} = \frac{s_{tj} - \hat{z}_{tj}}{\sigma_{tj}} \quad (20)$$

By using the equations (17), (18), (19) and (20), the retailer's profit maximization problem is reformulated into the equations (9), (10), (14), (15), (16), (17), (18), (19) and (20). The supplier's decision problem is a mixed integer program and the retailer' decision problem is a nonlinear programming problem (NLP) that can be solved by a general purpose solver.

4.2 Solution algorithm for bilevel programming

This section shows the solution algorithm for the multi-period bilevel supply chain model which is formulated as the nonlinear bilevel programming problem. In the algorithm, the supplier's problem is solved with the retailer's fixed order quantity Q_{tj}, and the retailer's problem is solved with the production quantity and the inventory quantity of $O_{tj} + I^s_{tj}$. By the iterative process, the Stackelberg equilibrium Q^*_{tj} is obtained. The retailer's objective function is formulated as the nonlinear programming problem. Therefore, we use IPOPT, the solver of General Algebraic Modeling System (GAMS). The supplier's problem is the mix-integer linear function. Therefore, we solve the supplier's problem by the branch and bound method.

The algorithm to solve the multi-period bilevel supply chain model is shown as follows.

Step 1 Set the production quantity and the inventory quantity $O_{tj} + I^s_{tj} \leftarrow 1(\forall t, \forall j)$, $l \leftarrow 1$ and $J^{\max}_s \leftarrow 0$. l is the index of the equilibrium solution and $J^{\max}_s$ is the supplier's the largest objective value. Go to Step 2.

Step 2 Solve the retailer's problem by using IPOPT with fixed production quantity and the inventory quantity of the products for the suppliers' decision. The obtained solution is $Q^l_{tj}(\forall t, \forall j)$. Go to Step 3.

Step 3 Solve the supplier's problem by the branch and bound method with the order quantity Q^l_{tj}, and the objective value is named as J^l_s. $J^{\max}_s \leftarrow J^l_s$ and $l^* \leftarrow l$ if $J^l_s > J^{\max}_s$. If the $O_{tj} + I^s_{tj}$ is not updated, equilibrium solution is $Q^{l^*}_{tj}$ and the algorithm is completed. Otherwise, $O_{tj} + I^s_{tj} \leftarrow O_{tj} + I^s_{tj} + 1$ and $l \leftarrow l + 1$, and then go to Step 2.

Through the iterative process of the solution algorithm, the equilibrium solution is obtained in the bilevel programming problem. In this study, the supplier is the leader in Stackelberg game. Therefore, the supplier's objective function is maximized in the equilibrium point.

5. Computational experiments

The multi-period bilevel supply chain model is analysed by some computational experiments and the model is verified in this section. In the model, the upper level is the supplier's problem which is formulated as the mixed-integer linear programming problem (MILP). The lower level is the retailer's problem which is formulated as the nonlinear programming problem (NLP). In the retailer's problem, the customer's demand is assumed to follow a normal distribution. The probability distribution is reformulated by the normalization in order to be computed by the solution algorithm shown in section 3. In the experiment, the end of period $T = 5$ and the number of the product types $J = 3$. The experiment was performed by Intel (R) Core(TM) i7-2700 CPU 3.50GHz with General Algebraic Modelling System (GAMS). Two kinds of solvers are used in the experiments. One is CPLEX used to solve MILP for the supplier. The other is the IPOPT used to solve the retailer's NLP. In the experiment, $\mu_{tj} = 50$, $\sigma_{tj} = 20$, $s_{1,j} = 10000$, $s_{2,j}, s_{3,j} = 20000$ and $s_{4,j}, s_{5,j} = 5000$. Tables 1, 2, 3 show the value of parameters which are special to product 1, 2 and 3 respectively.

Table 1 Parameters for product 1.

Period	1	2	3	4	5
p_{t1}	300	300	300	300	300
h^r_{t1}	15	15	30	30	15
g_{t1}	120	120	120	120	120
c_{t1}	60	60	60	60	60
h^s_{t1}	20	15	30	15	15
w_{t1}	250	250	250	250	250

Table 2 Parameters for product 2.

Period	1	2	3	4	5
p_{t2}	290	290	290	290	290
h^r_{t2}	15	30	30	15	15
g_{t2}	116	116	116	116	116
c_{t2}	50	50	50	50	50
h^s_{t2}	20	15	30	15	15
w_{t2}	230	230	230	230	230

Table 3 Parameters for product 3.

Period	1	2	3	4	5
p_{t3}	270	270	270	270	270
h^r_{t3}	15	15	15	30	30
g_{t3}	108	108	108	108	108
c_{t3}	40	40	40	40	40
h^s_{t3}	15	15	15	30	30
w_{t3}	240	240	240	240	240

The computational experiments are performed with the parameters in Tables 1, 2, and 3. In the supplier's problem, the initial quantity of the inventory $I^s_{0,j} = 150$. They are obtained by the optimization in the bilevel programming problem. The supplier can produce only one type of product item in each period by the constraint (4). Table 4 shows the computational results of the order quantity and the production quantity. According to the results, the retailer decides larger amount of order quantity when the inventory holding cost is lower in order to decrease the total inventory holding costs. In the numerical experiments, the inventory holding cost is lower than the opportunity cost to the retailer. Therefore, the retailer prefers to increase the quantity of inventories so as not to increase the opportunity loss costs. On the other hand, the supplier can produce only one type of items in each period by the constraint (4). Therefore, the supplier decides the order quantity in order to maximize its total profit. According to the results in Table 4, the supplier decides larger amount of products in order to decrease the inventory holding costs.

Table 5 shows the supplier's and the retailer's objective values. In the Stackelberg equilibrium conditions, the retailer's objective value is negative. Although the negative objective value is not realistic, the numerical results are valid because the supplier's objective value becomes the largest at the equilibrium point.

Table 4 Computational results of order quantity and production quantity.

Period	1	2	3	4	5
Q_{t1}	78	49	42	48	22
Q_{t2}	78	42	49	55	17
Q_{t3}	76	49	49	42	21
O_{t1}	0	0	90	0	0
O_{t2}	0	19	0	72	0
O_{t3}	87	0	0	0	0

Table 5 Computational results of the profit for supplier and retailer.

Objective	Values
J_s	91587
J_r	16942
Total	108529

We conduct the computational experiments when the leader-follower relationship can be changed dynamically. Then, the next three cases are conducted.

Case 1: The supplier is the leader in all periods.
Case 2: The retailer is the leader in all periods.
Case 3: The leader is started from the supplier and the leader is changed from the supplier to the retailer at the start of period 3.

In the Stackelberg game where the leader is the retailer, the retailer's problem is the upper problem and the supplier problem is the lower problem. In this case, the supplier at first makes its decision in order to maximize its own profit and then the retailer makes decisions with the supplier's decision variable in order to maximize the retailer's total profit.

In the Stackelberg game where the leader is changed in period 3, the supplier is the leader in periods 1 and 2. The supplier makes a decision in order to maximize its own profit for whole periods. Then, the leader is changed from the supplier to the retailer, and the retailer makes decision as the leader in period 3. In this case, the decision variables of the supplier and the retailer in periods 1 and 2 are obtained and used in order to solve the Stackelberg game where the retailer is the leader in period 3, 4 and 5.

The computational experiments are performed with the parameters in Tables 1, 2, 3 which are the same condition in the experiment of the Stackelberg game where the leader is the supplier.

Tables 6, 7, 8 show the computational result of the experiments for Case 1, Case 2, Case 3, respectively. According to the table, the total profit is the largest if the leader is changed from the supplier to the retailer. In the Stackelberg game where the supplier is the leader, the supplier's inventory cost is small. On the other hand, the supplier's setup cost is large. In this case, the setup cost is the lowest priority in the supplier's decision making in period 5. Therefore, the supplier makes decisions in order to increase the high-priority decision variable, for example, the amount of production or inventory. Moreover, in the Stackelberg game where the supplier is the leader, the retailer makes a decision in order to maximize the retailer's profit. In this case, the retailer makes a decision without considering the supplier's setup cost. Therefore, the setup cost cannot be decreased in this situation.

In the Stackelberg game where the retailer is the leader, the retailer makes decisions with the supplier's decision making which is conducted first. In this case, the retailer prefers the point where the order quantity is satisfied with the customer's demand. Therefore, the supplier is required to produce in order to satisfy the retailer's order quantity and cannot be considered the setup cost. However, the retailer should make decisions with the supplier's decision making. Therefore, the total profit is smaller than that in a Stackelberg game where the leader is the supplier.

On the other hand, the setup cost is the smallest in the situation where the leader is changed in period 3. In this situation, the retailer makes decisions with the supplier's decision making after changing the leader from the supplier to the retailer.

Table 6 Computational results of Case 1 (the leader is the supplier)

Objective function	Supplier	Retailer
Production cost	−13,443	
Inventory holding cost	−12,338	−6,548
Setup cos	−55,000	
Opportunity loss cost		−5,469
Wholesale cost	172,368	−172,368
Revenue		201,328
Total profit	91,587	16,942

Table 7 Computational results of Case 2 (the leader is the retailer)

Objective function	Supplier	Retailer
Production cost	−13,439	
Inventory holding cost	−12,457	−6,578
Setup cost	−55,000	
Opportunity loss cost		−5,476
Wholesale cost	172,353	−172,353
Revenue		201,310
Total profit	91,457	16,904

Table 8 Computational results of Case 3 (the leader is changed at period 3)

Objective function	Supplier	Retailer
Production cost	−10,750	
Inventory holding cost	−12,120	−5,380
Setup cost	−35,000	
Opportunity loss cost		−10,322
Wholesale cost	161,133	−161,133
Revenue		201,328
Total profit	103,263	12,360

Table 9 Comparison of performance in each case

leader	setup cost	J_s	J_r	Total
supplier	55,000	91,587	16,943	108,530
retailer	55,000	91,457	16,904	108,361
change	35,000	103,263	12,360	115,623

6. CONCLUSION

In this study, the multi-period bilevel supply chain model is formulated. In the model, the supplier and the retailer make decisions in the Stackelberg game in which the supplier's problem is the upper level, and the retailer's problem is the lower level. In order to compute the equilibrium solution by the experimental method, the retailer's problem is reformulated by normalization of the probability distribution which expresses the customer's demand. The solution algorithm is shown in order to solve the equilibrium solution in the nonlinear bilevel programming problem, and the model's validity is shown by the numerical experiments. Moreover, the comparison with some situation, the total profit is the largest in Stackelbeg game where the leader is changed from the supplier to the retailer in period 3. In the future works, we will develop the solution algorithm in order to be applied to more a large scale problem and solve the problem in a small computational time. Moreover, we will consider better scenarios for a Stackelberg game where the leader is changed in some period by some numerical experiments.

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